NASA TT F-9739

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N66-11612

(ACCESSION NUMBER) (THRU)

7 1

(PAGES) (CODE)

33

(NASA CR OR TMX OR AD NUMBER) (CATEGORY)

FACILITY FORM 602

Translation of "Issledovaniye teploobmena pri plavlenii l'da v svobodnom potoke". Kolodil'naya Tekhnika, Vol.37, No.4, pp.23-5, 1960.

GPO PRICE $ _____

CFSTI PRICE(S) $ _____

Hard copy (HC) 1.00

Microfiche (MF) .50

ff 653 July 65

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON OCTOBER 1965

INVESTIGATION OF HEAT TRANSFER DURING MELTING OF ICE UNDER FREE FLOW CONDITIONS

V.Filatkin*

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The heat transfer of melting ice in freely flowing water at fixed temperature was investigated by visual observations and mathematical means. The melting time of standardized ice cubes is plotted as a function of temperature and a criterial equation is derived for calculating the heat transfer in which the Nusselt group is made dependent on the Grashof-Prandtl group.

Author

Research into the process of ice melting and, in particular, of heat transfer during the melting, is of major importance.

Heat transfer during melting was the subject of the major work by A.G. Tkachev (Bibl.1). On the basis of theoretical and experimental investigations, this author recommended certain working formulas.

These investigations concerned cylinders and spheres of ice and ethylene glycol. The experimental findings were analyzed with the aid of the similitude theory. In the coordinates of $\overline{Nu}\,\frac{Fo}{K}$ - log (Gr·Pr) the experimental points are generalized by a straight line parallel to the abscissa. Thus, A.G.Tkachev's work proves that the $\overline{Nu}\,\frac{Fo}{K}$ criterion is independent of the Gr·Pr criterion. In analyzing the graphic function $\overline{Nu}\,\frac{Fo}{K} = f(Gr \cdot Pr)$ given in his work, a considerable scatter of the experimental points (20 - 30%) will be noted.

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** Numbers in the margin indicate pagination in the original foreign text.

A.G.Tkachev's criterial equation of heat transfer during the melting of ice in a free fluid flow has the following form:

$$\overline{Nu}\frac{Fo}{K}=0.32, \tag{1}$$

where

$\overline{Nu}$ = mean Nusselt number for convective heat transfer during melting;

$Fo = \frac{a\tau}{a^2}$ = Fourier criterion;

$K = \frac{\varphi}{c\bar{\Theta}_0}$ = criterion of phase transition.

Equation (1) was derived on the basis of an investigation of ice in the form of spheres and cylinders, and therefore cannot be applied to cases of melting of ice of other shapes without prior verification.

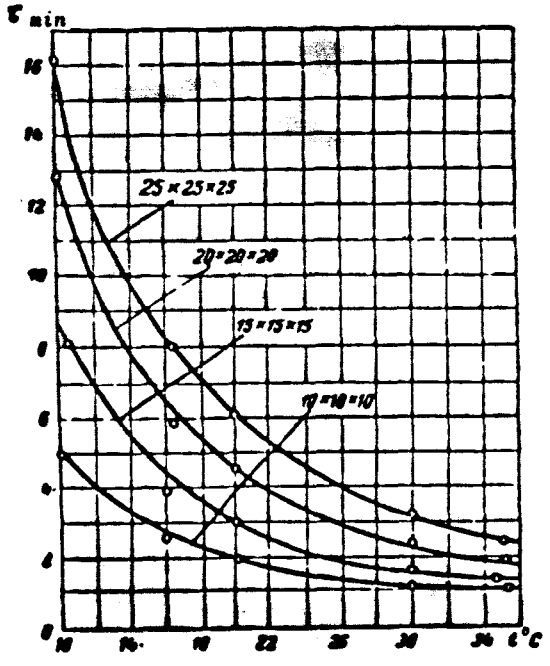

Fig.1 Melting Time of Ice Cubes as a Function of Temperature

The Laboratory of Heat Transfer of the Chair of Theoretical Principles of Heat and Cold Engineering, LTIKhP, made investigations on the melting of small

cube-shaped lumps of ice in four sizes: 25, 20, 15, and 10 mm.

The melting of ice in water was done in a 7-liter glass vessel. The water temperature was varied from 10 to 35°. The initial temperature of the lumps of ice was $t_w = 0°C$. The investigation pertained to the process of melting of a single small cube of ice in freely flowing water at a fixed temperature. The time was measured with a stopwatch and the water temperature, with a laboratory thermometer graduated in 0.1°C.

The end of melting of the lump of ice was determined visually. This investigation revealed that the melting process of ice proceeds more intensively on the vertical sides. The experimental findings were used to plot curves of the melting time of ice cubes as a function of temperature $\tau = f(t)_e$ (Fig.1). As can be seen from the graphs, the curves satisfactorily approximate the experimental points pertaining to a specific size of the ice cube. The melting time of an ice cube increases with increasing size of the cube and with decreasing ambient temperature. /24

The findings were analyzed with the aid of the similitude theory. The results of the calculations are presented in the Table.

The Table employs the following notations:

$$\lambda_0 = \frac{2\lambda_{fm}\vartheta_0}{\nu_{fm}\varphi\gamma_w} = \text{dimensionless thickness of boundary layer;}$$

$$Nu_0 = 0.6(Gr_{fm}Pr_{fm})^{\frac{1}{4}} = \text{Nusselt number for free motion without change of state;}$$

$$Gr_{fm} = \frac{g\ell^2\Delta t\beta_f}{\nu_{fm}^2} = \text{Grashof number;}$$

β_f = fictitious coefficient of volume expansion.

The values of β_f and $\frac{\overline{Nu}}{\overline{Nu}_0}$ in this investigation were taken from A.G. Tkachev's work.

Temp. of Water and temp. diff. betw. Water and Ice t_{ice}: ϑ_0, °C	Mean temp. of boundary layer $t_{/m}$, °C	Cube size l, mm	Melting time τ, min	Kinematic Viscosity at $t_{/m}$ · 10^6, m²/sec	Heat conduction of Water at $t_{/m}$ $\lambda_{/m}$, kcal/hr. deg.	Dimensionless thickness of boundary layer λ_0	Therm. Diffusivity of Water at $t_{/m}$ $a_{/m}$ · 10^6	Fictit. coeff. of volume expansion $\beta_{/m}$ · 10^3, 1/°C	$Pr_{/m}$	$K = \frac{\gamma}{\alpha\vartheta_0}$	$Gr_{/m}$	$Gr_{/m} \cdot Pr_{/m}$	Nu_ϑ	$\frac{\bar{Nu}}{Nu_\vartheta}$	$\bar{Nu}$	Po	$\frac{\bar{Nu}}{K} Po$
10.0	5.0	25	16.117	1.547	0.484	0.0236	4.82	2.0	11.59	8.0	12800	14.85·10⁴	11.7	0.95	11.1	0.207	0.287
10.0	5.0	20	11.65	1.547	0.481	0.0236	4.82	2.0	11.59	8.0	6570	7.62·10⁴	9.95	0.95	9.45	0.234	0.276
10.05	5.025	15	7.85	1.546	0.481	0.0237	4.82	2.0	11.59	7.96	2760	3.22·10⁴	8.05	0.95	7.65	0.280	0.269
10.07	5.035	10	4.93	1.545	0.494	0.0237	4.82	2.0	11.53	7.95	827	0.956·10⁴	5.93	0.95	5.6ᵉ	0.398	0.293
16.5	8.25	25	8.45	1.390	0.491	0.0410	4.90	2.8	10.25	4.85	36600	3.76·10⁴	14.9	0.90	13.4	0.110	0.314
16.1	8.05	20	5.618	1.400	0.490	0.0426	4.895	2.8	10.33	4.97	18600	1.86·10⁴	12.5	0.91	11.4	0.115	0.264
16.1	8.05	15	4.059	1.400	0.490	0.0426	4.895	2.8	10.33	4.97	7600	1.785·10⁴	10.0	0.91	9.1	0.147	0.269
16.05	8.025	10	2.446	1.411	0.490	0.0425	4.895	2.8	10.34	4.99	2250	0.232·10⁴	7.38	0.91	6.7	0.200	0.268
30.08	15.04	15	1.8[illegible]	1.155	0.503	0.0295	5.05	3.9	8.26	2.66	51500	4.25 ·10⁴	15.35	0.85	13.1	0.0675	0.332
30.0	15.00	20	2.634	1.156	0.504	0.0295	5.05	3.9	8.27	2.67	121000	10.0 ·10⁴	19.0	0.85	16.2	0.0551	0.336
30.08	15.04	25	3.231	1.155	0.505	0.0295	5.05	3.9	8.26	2.66	238000	19.65·10⁴	22.6	0.85	19.2	0.0435	0.314
20.08	10.04	10	1.835	1.335	0.494	0.0574	4.94	4.0	9.51	3.98	4630	0.44·10⁴	8.67	0.88	7.61	0.151	0.290
20.08	10.04	15	3.089	1.305	0.494	0.0574	4.91	4.0	9.51	3.98	15600	1.49·10⁴	11.75	0.88	10.35	0.113	0.291
20.0	10.0	20	4.583	1.306	0.491	0.0572	4.94	4.0	9.52	4.00	36800	3.5·10⁴	14.45	0.88	12.7	0.0943	0.300
20.1	10.05	25	6.10	1.305	0.494	0.0574	4.94	4.0	9.51	3.98	72200	6.87·10⁴	17.3	0.88	15.2	0.0801	0.307

The data in the Table were used to construct, in logarithmic coordinates, the graph (Fig.2) of the functional dependence

$$\bar{Nu}\frac{Fo}{K} = f(Gr_{fm} \cdot Pr_{fm}).$$

As can be seen from this diagram, the experimental points are satisfactorily generalized by the straight line 1. Their maximum deviation is 8.3% and the mean scatter, 3%. Line 2 was plotted according to the criterial equation (1).

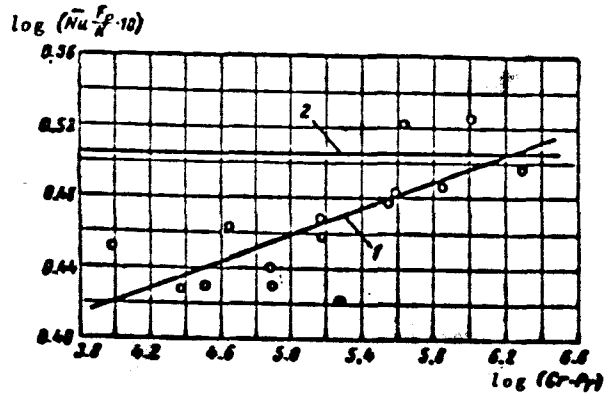

Fig.2 Results of Generalized Treatment of Experimental Findings on the Melting of Ice Cubes

The experimental points mostly lie below line 2; their maximum distance /25 from this line is 16.6% and the mean distance, 8.8%.

It is worth noting that the actual melting time of the ice cubes is as a rule shorter than the theoretical time determined from eq.(1).

The melting process of ice cubes is characterized more precisely by the criterial equation which we derived on the basis of an analysis of experimental findings by the method of least squares:

$$\bar{Nu}\frac{Fo}{K} = 2.0(Gr \cdot Pr)_m^{0.248}. \qquad (2)$$

Relation (2) holds true for the following intervals of variation in simili-

tude criteria:

$$Gr \cdot Pr_m = 9.6 \cdot 10^4 \div 19.7 \cdot 10^4$$

$$\bar{Nu} \frac{Fo}{K} = 0.26 \div 0.34.$$

The chief difference between the criterial equation (2) and eq.(1) lies in that, in eq.(2) the $\bar{Nu} \frac{Fo}{K}$ group depends on the $(Gr \cdot Pr)_m$ group, whereas eq.(1) establishes the independence of the $\bar{Nu} \frac{Fo}{K}$ number from the Gr·Pr number.

This divergence is due to the insufficient accuracy of the experiments on whose basis eq.(1) was composed.

CONCLUSIONS

The generalized criterial equation recommended by A.G.Tkachev may also be applied to the case of the melting of cube-shaped lumps of ice, but then the error of the findings exceeds 20%.

The more precise criterial equation, derived by means of the method of least squares, can be used for the case of the melting of ice cubes in water.

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